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Variation in Round Goby Feeding Interactions in Near-Shore Lake Michigan Based on Three Trophic Indicators

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VARIATION IN ROUND GOBY FEEDING INTERACTIONS IN NEAR-SHORE LAKE MICHIGAN BASED ON THREE TROPHIC INDICATORS

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ABSTRACT

Henebry, Michael L. M.S., Purdue University, August 2014. Variation in Round Goby Feeding Interactions in Near-shore Lake Michigan Based on Three Trophic Indicators. Major Professor: Tomas Höök.

Understanding trophic interactions of non-native species is key to elucidating their potential ecological role in newly-invaded ecosystems. The Great Lakes region has long been characterized by a high rate of invasive species establishment. Round Goby (*Neogobius melanostomus*) were first detected in Lake Michigan in 1994, and have since increased dramatically in abundance. While past studies of Round Goby in Lake Michigan have primarily focused on specific regions and habitats, Lake Michigan is a large, diverse system and Round Goby trophic interactions may vary across regions and over time. During May, July, and September 2010-2011, we collected Round Goby (via 2-hr bottom set, micromesh gillnets) and their potential benthic invertebrate prey at ten sites throughout much of Lake Michigan. In the laboratory, we identified and enumerated diet contents and potential prey items, and homogenized gobies for subsequent fatty acid and $\delta^{13}C$ and $\delta^{15}N$ stable isotope quantification. These three trophic indicators provide complementary information regarding trophic interactions. Diet content analysis and stable isotope analyses are well-established approaches and provide detailed quantification of recent (i.e. short term) prey consumption and long-term indexing of production pathways, respectively. In contrast, fatty acid analysis is a relatively novel method for describing trophic interactions over an intermediate temporal scale. Results

indicate diets, fatty acids, and stable isotope signatures of gobies vary individually (by size), seasonally, and spatially. Specifically, the three trophic indicators collectively indicate that Round Goby display a greater reliance on near-shore benthic pathways in western Lake Michigan versus a greater reliance on pelagic pathways in eastern Lake Michigan. This spatial pattern may reflect differential prey production related to physical processes and substrate, i.e., relatively high frequency of upwelling events and preponderance of rocky substrate in western Lake Michigan versus downwelling events and predominately sandy substrate in much of eastern Lake Michigan.

EXTENDED ABSTRACT

Understanding trophic interactions of non-native species is key to elucidating their potential role in novel ecosystems. Round Goby (*Neogobius melanostomus*) were first detected in Lake Michigan in 1994, and have since increased dramatically in abundance. While past studies of Round Goby in Lake Michigan have primarily focused on specific regions and habitats, Lake Michigan is a large, diverse system and Round Goby trophic interactions may vary across regions and over time. We hypothesize that Round Goby foodweb interactions will vary significantly and spatio-temporally. During May, July, and September 2010−2011, we collected Round Goby (via 2-hr bottom set, micromesh gillnets) and their potential benthic invertebrate prey at ten sites throughout Lake Michigan. Samples were either frozen or preserved in formalin (10% formaldehyde solution) for future examination. In the laboratory, we identified and enumerated diet contents and potential prey items, and homogenized gobies for subsequent fatty acid and

$\delta^{13}C$ and $\delta^{15}N$ quantification. These three trophic indicators provide complementary information regarding trophic interactions. Diet content analysis and stable isotope analyses are well-established approaches and provide detailed quantification of recent prey consumption and long-term indexing of production pathways, respectively. In contrast, fatty acid analysis is a relatively novel method for describing trophic interactions over an intermediate temporal scale. Non-metric multidimensional scaling (nMDS) and $\delta^{13}C$ versus $\delta^{15}N$ biplots were used to visualize round goby trophic relationships. Analysis of similarity (ANOSIM) was subsequently used to test for significant differences among sites and sampling dates. Results indicate diets, fatty acids, and stable isotope signatures of gobies vary individually (by size), seasonally, and spatially. Specifically, the three trophic indicators collectively indicate that Round Goby display a greater reliance on near-shore benthic pathways in western Lake Michigan versus a greater reliance on near-shore pelagic pathways in eastern Lake Michigan. This spatial pattern may reflect differential prey production related to physical processes and substrate, i.e., relatively high frequency of upwelling events and preponderance of rocky substrate in western Lake Michigan. Overall, inter-annual variability was low and our findings support the concomitant use of diets, fatty acids, and stable isotopes to explore trophic interactions.

CHAPTER 1. VARIATION IN ROUND GOBY FEEDING INTERACTIONS IN NEAR-SHORE LAKE MICHIGAN BASED ON THREE TROPHIC INDICATORS.

1.1 Introduction

While foodwebs are often depicted as static in space and time, inter-specific predator-prey interactions (i.e., individual foodweb linkages) can vary ontogenetically (Werner et al. 1983; Warren and Lawton 1987; Woodward and Hildrew 2002), spatially (Closs and Lake 1994; Polis et al. 1997; Warren 1989; Winemiller 1990) and seasonally (Menge and Sutherland 1976; Warren 1989; Winemiller 1990; Closs and Lake 1994). In large aquatic systems, dominant primary production and consumption pathways (i.e., the bottom of the foodweb) may vary spatially and temporally and thereby differentially affect composition and condition of lower trophic levels (e.g., Brooks and Edgington 1994). Physical processes may mediate magnitude and characteristics of primary production (e.g., through nutrient delivery, re-suspension and distribution). Consistent physical features (e.g., sediment characteristics) and prevailing conditions (e.g., water currents and gyres) may continuously structure foodwebs, while episodic hydrological events, such as river discharges and upwellings, may vary temporally in duration and intensity (Ayers et al. 1958; Beletsky and Schwab 2001; Schwab and Beletsky 2003) and affect local areas or broad regions (Schelske et al. 1971; Bell and Eadie 1983; Lee and Hawley 1998; Lou et al. 2000; Eadie et al. 2002). Ultimately, such structuring processes may not only lead to spatio-temporal differences in primary producers and consumers,

but may also be reflected in the space- and time-specific diets and dietary signatures of secondary and tertiary consumers as energy is passed up the food chain.

Invasive species introductions are often linked to community compositional changes (Mills et al. 1993; Dextrase and Mandrak 2006; Mercado-Silva et al. 2006). Such changes may contribute to drastically altered foodwebs and trophic regimes (Horppila et al. 1998; Kuhns and Berg 1999; Vander Zanden et al. 1999; Janssen and Jude 2001; Vanderploeg et al. 2002; Hecky et al. 2004). However, given the potential for variation in foodweb structure across space and time, the trophic role and influence of invasive species may similarly vary. For example, while several invasive species have become established and altered trophic pathways in Lake Michigan, particularly the near-shore zone (Madenjian et al. 2002), it should not be assumed that their ecological roles are uniform throughout the lake. In particular, ecological interactions and invasive species effects may differ across divergent habitats (e.g., sandy versus rocky substrates).

Near-shore areas are important for many organisms throughout the Laurentian Great Lakes, as they support relatively high productivity, diversity, and biomass (Barton and Hynes 1978; Griffiths 1993; Howell et al. 1996; Haynes et al. 1999; Ackerman et al. 2001; Mackey and Goforth 2005; Depew et al. 2006), but tend to be highly impacted by anthropogenic activities (Madenjian et al. 2002; Meadows et al. 2005; Goforth and Carman 2009). Additionally, near-shore areas serve as nursery habitats for larval and juvenile fishes (Goodyear et al. 1982; Roseman et al. 2005; Höök et al. 2008), but also constitute important habitat for adult fishes (Miller and Holey 1992; Lane et al. 1996; Mackey and Goforth 2005; Goforth and Carman 2009). Moreover, near-shore foodweb interactions may have changed spatially and temporally in light of recent species

invasions (Rennie et al. 2009). For example, several recent invaders, including dreissenid mussels (Zebra Mussel, *Dreissena polymorpha*; Quagga Mussel, *D.rostriformis bugensis*) and Round Goby (*Neogobius melanostomus*), have contributed to shunting of energy from the pelagic to the benthic near-shore via biomass accumulation (Krieger 1992; Vanderploeg et al. 2002; Hecky et al. 2004; Turschak et al. 2014). These foodweb changes may have increased the relative importance of near-shore areas for lake-wide consumer production.

Round Goby are benthic fishes from the Ponto-Caspian region, which were first introduced to the Great Lakes basin through ballast water discharge during the late 1980's (Jude et al. 1992; Charlebois et al. 1997; Charlebois et al. 2001). They expanded throughout the Great Lakes during the 1990's (Ricciardi and MacIsaac 2000; Clapp et al. 2001) and were first detected in Lake Michigan in 1993 (Marsden and Jude 1995). As their abundance increased, Round Goby preyed upon, competed with, and subsequently displaced multiple native species (e.g. several sculpin, darter, and invertebrate species) (Crossman et al. 1992; Marsden and Jude 1995; Jude et al. 1995; Dubs and Corkum 1996; French and Jude 2001; Janssen and Jude 2001; Vanderploeg et al. 2002; Lauer et al. 2004; Balshine et al. 2005; Cooper et al. 2009). Round Goby are voracious predators, which often consume a vastly different prey assemblage based on location and availability (Charlebois et al. 2001). However, when available, Round Goby apparently prefer chironomid larvae over various other prey, including dreissenid mussels (Coulter et al. 2011). Additionally, Round Goby have become important prey for several native and commercially-important piscivores such as Lake Trout (*Salvelinus namaycush*) and Smallmouth Bass (*Micropterus dolomieu*) (Steinhart et al. 2004; Truemper and Lauer

2005; Dietrich et al. 2006; Jacobs et al. 2010; Reyjol et al. 2010; Taraborelli et al. 2010; Madenjian et al. 2011).

Round Goby feeding interactions have been described at local scales (i.e. Janssen and Jude 2001; Andraso et al. 2011), but there has not been a comprehensive, broad-scale assessment of Round Goby feeding interactions for any Great Lake (Charlebois et al. 2001). Moreover, near-shore areas are quite different physically and chemically in various regions of Lake Michigan, which likely promote different feeding interactions. Studies of broad-scale feeding interactions and foodweb structure are often logistically difficult due to need for sampling across large areas over extended time periods. Likewise, piecing together information from local and regional studies may be informative, but may not give a true representation of foodweb interactions over space and time due to methodological variability among studies. Laboratory studies have suggested feeding preferences and likely trophic linkages between Round Goby and near-shore prey (Bauer et al. 2007; Coulter et al. 2011), but such relationships are likely not directly transferable to trophic relationships at specific *in situ* locations.

Novel approaches have emerged to examine aquatic foodweb interactions, including fatty acid signatures (FAS) and $\delta^{13}C$ / $\delta^{15}N$ stable isotope ratios (SIR). Consumers are not able to synthesize several fatty acids, and instead attain many fatty acids through their diet. Primary producers differ in their synthesis and expression of different fatty acids (Kelly and Scheibling 2012). Thus, the relative concentrations of specific fatty acids in consumers' tissues may indicate benthic (i.e. detritus, bacteria, and diatoms, typically enriched in palmitic acid (C16:1n-7) and eicosapentaenoic acid (EPA C20:5n-3)) or pelagic (i.e. zooplankton and phytoplankton taxa typically enriched in

docosahexaenoic acid (DHA C22:6n-3)) trophic pathways and reflect differential prey item consumption and assimilation (Graeve et al. 1994; Napolitano 1994; Czesny et al. 2011). Thus, relative percentages of multiple fatty acids retained in predator tissues can provide meaningful characterization of fish diets over intermediate time horizons (4−12 weeks; Kirsch et al. 1998; Dalsgaard et al. 2003; Budge et al. 2006; Budge et al. 2011; Czesny et al. 2011). In contrast, $\delta^{13}C$ / $\delta^{15}N$ SIR provide a relatively long-term (i.e. slow fractionation and turnover, Tieszen et al. 1983) and stable (France 1995) index of trophic position (i.e. relative food chain level) and diet source (Peterson and Fry 1987; Wada et al. 1991; Mitchell et al. 1996; Post 2002; Campbell et al. 2003; Havens et al. 2003; Fry 2006). Pelagic diet signatures are generally depleted in $\delta^{13}C$, while benthic signatures are enriched (Fry 1991). Additionally, $\delta^{15}N$ signatures represent relative trophic levels, with approximately 3−4% enrichment of $\delta^{15}N$ with each increase in trophic level (Hobson et al. 1994; Post 2002).

Many contemporary foodweb studies have employed one or two trophic indicators to describe feeding interactions. However, trophic indicators vary greatly in their temporal and taxonomic resolution and may thereby reveal differential trophic linkages. For example, various trophic indicators quantify feeding interactions at different timescales (from < 1 day to > 3 months; Budge et al. 2002; Iverson et al. 2002; Pasquaud et al. 2008; Czesny et al. 2011; Davis et al. 2012; Rush et al. 2012). While diet content analysis may allow for describing prey consumption at fine taxonomic resolution, prey-specific digestion and retention rates may bias prey consumption analyses. In contrast, FAS and SIR quantify prey incorporated by consumers, independent of digestive rate; however, the taxonomic resolution of these methods is relatively limited. Ultimately,

FAS and $\delta^{13}C$ / $\delta^{15}N$ SIR may complement traditional gut content analysis and collectively provide a comprehensive approach to examine feeding interactions over multiple timescales (Budge et al. 2002; Iverson et al. 2002; Pasquaud et al. 2008; Czesny et al. 2011; Davis et al. 2012; Rush et al. 2012).

Herein, we combine three trophic indicator methods (i.e. digestive tract analysis, fatty acids, and $\delta^{13}C$ / $\delta^{15}N$ stable isotopes) to describe Round Goby feeding patterns in near-shore areas of eastern and western Lake Michigan to elucidate spatial, seasonal, and size-related differences. We hypothesize that Round Goby foodweb interactions will vary spatially, temporally, and as a function of fish size in Lake Michigan.

1.2 Methods

1.2.1 Field Collections

Eleven sites were sampled throughout much of Lake Michigan during 2010 and 2011 (Table 1; Figure 1). Sites were selected to provide wide spatial distribution and varying substrate types. Samples were obtained from sites FP, WB, HP, DR, CA, MC, and SA in May, July, and September 2010 and from sites MK, FF, and SB in July and September 2010 only. Sites FP, HP, MC, and MK were also sampled in May, July, and September 2011 (Figure 1).

Potential near-shore benthic prey items were captured using a petite PONAR at sandy sites (PONAR area=0.053m^2) and SCUBA (self-contained underwater breathing apparatus) benthic scraping, coupled with a pneumatic airlift system (Mackey 1972; Pearson et al. 1973) at rocky sites. PONAR samples were collected in triplicate at all

depths (3m, 7–9m, and 14–16m) during 2010 and 2011 and a complete complement of three airlift samples was collected at FP, HP, and CA once during July 2010. Round Gobies and other fish species were collected via 2hr bottom-set, parallel- (most net sets) and perpendicular-to-shore micromesh gillnet sets (6.0mm, 8.0mm, 10.0mm, and 12.0mm bar mesh sizes, 10m of each mesh size per gillnet). Past studies indicate that Round Goby diets vary with individual size (e.g., review by Kornis et al. 2012), and to describe such size-based variation, Round Gobies were targeted per *a priori* selected size classes (i.e. <60mm, 60−100mm, and >100mm; 15−20 individuals per size class) to quantify size-related diet patterns. Fishes were either blotted dry and frozen on dry ice prior to subsequent storage in a -80°C freezer for fatty acid analyses or frozen in water on ice prior to storage in a -20°C freezer for later examination.

1.2.2 Laboratory Analyses

Round Goby diets were examined in the laboratory using traditional diet content analysis. All Round Gobies were measured for length (i.e. SL and TL; ± 1mm) and weight (± 0.001g). Fish were subsequently dissected and whole digestive tracts were removed and stored in 95% ethanol. Since Round Goby do not have a clearly defined stomach, entire digestive tract contents were identified to the lowest practical taxonomic level, enumerated, and photographed using a dissecting microscope (Olympus SZ61, Unitron Z850 or Leica MS5) and microscope camera (Micrometrics 318CU). Lengths of prey items in the digestive tract were measured using ImageJ software. Measurements were compared to published species-specific biomass-at-size regressions to estimate percent dry diet biomass composition per food item per fish (Dumont et al. 1975; Benke

et al. 1999; Sabo et al. 2002). In addition, entire digestive tract contents were dried for 3 days at 70°C for diet biomass estimation.

Digestive tracts were removed from fishes preserved at -80°C, and individual fish were homogenized using a Waring commercial blender to quantify Round Goby fatty acid signatures. We analyzed 3–20 gobies per size class from each sampling event. After homogenization, lipids were extracted from fish tissue (Folch et al. 1957), fatty acids were transmethylated (Metcalfe and Schmitz 1961), and fatty acid signatures were analyzed using a gas chromatography mass spectrometer (GC/MS: Agilent 6890 Gas Chromatograph, Agilent Technologies Inc., Wilmington, DE) with a mass selective detector (Agilent model 5973), capillary column (Omegawax model 320, 30m x 0.32mm x 0.25µm, Supleco, Bellefonte, PA), and autoinjector (Hewlett Packard model 7863). Fish tissue was weighed (~1g wet, 0.3g dry), solvent (chloroform/methanol/BHT solution) was added, and samples were placed on ice. Samples were homogenized (~1 minute) with an Omni homogenizer and remained on ice during this process. Samples were stored on ice after homogenization for further processing. The homogenizer was routinely cleaned between samples using reverse osmosis (i.e. RO) water, blotted dry, cleaned with the solvent, and blotted dry again. Samples were vacuum filtered, transferred to glass tubes, and placed on ice. $MgCl_26H_2O$ (4ml) was added and sample tubes were filled with nitrogen gas. Sealed samples were vortexed for 1 minute, more nitrogen gas was added, and the tube was resealed. Tubes were then stored at room temperature for 1 day to allow samples to separate into 2 layers. The bottom phase was removed and transferred to a homogenization tube. Solvent was evaporated using nitrogen gas in a water bath. Chloroform was added to samples, and samples were left to evaporate under nitrogen gas

in a water bath to ~1–2ml. Samples were transferred to pre-weighed glass tubes using chloroform. Samples were evaporated using nitrogen gas in a water bath until samples showed no detectable weight changes. Chloroform was added (~1ml), and then tubes were filled with nitrogen gas, sealed, and placed in a -80°C freezer until the next day. Chloroform was then evaporated from lipid content in each sample using nitrogen gas. An internal standard (C19:0, Nu Check Prep Inc., Elysian, MN) was added proportionately based on lipid volume (8mg standard / 50mg lipid) and evaporated with nitrogen gas. NaOH in methanol (0.5M, 1.5ml) was added, and tubes were filled with nitrogen gas and capped. Samples were incubated at 80°C for 1 hour. Samples were cooled to room temperature and borontrifluoride methanol (2ml) was added. Tubes were filled with nitrogen gas and capped. Samples were incubated at 80°C for 30 minutes and cooled to room temperature. Hexane (1ml) was added to samples and tubes were vortexed (sealed). Water (1ml) was added to each sample and tubes were vortexed (sealed). Hexane phases were extracted and transferred to new tubes with sodium sulfate. Hexane (1ml) was added to sample tubes and vortexed (sealed). The hexane phases from sample tubes were extracted and added to the new sodium sulfate tubes containing the previously extracted hexane phases. Sealed samples were vortexed and hexane phases were transferred to new 4ml vials. Nitrogen was added to each of the new sample hexane phase vials and vials were stored at -80°C (sealed) until GC/MS runs. GC/MS results were interpreted from quantitative fatty acid peaks that appear at predictable retention times.

To quantify Round Goby $\delta^{13}C$ and $\delta^{15}N$ stable isotope signatures, whole fish, minus the digestive tract, were homogenized using a Waring commercial blender (up to 3 fish per size class per sampling event). Samples were then lyophilized with a LABCONCO freeze dry system for 1−3 days. Dry tissue (3−4mg per sample) was weighed into tin capsules, compressed into cubes, and kept in a desiccator until mass spectrometer analysis. Stable isotopes were analyzed using a Finnigan MAT delta S SIR-MS, with Carlo Erba NA 1500 NCS elemental analyzer front end and ConFlo II interface. Nitrogen (N_2) and carbon dioxide (CO_2) peaks were centered before each stable isotope run; standard deviations are typically 0.05% for $\delta^{13}C$ and 0.15% for $\delta^{15}N$. Standards (N_2: air, CO_2: Pee Dee Belemnite carbonate) were run with samples to compare known $\delta^{13}C$:$\delta^{12}C$ and $\delta^{15}N$:$\delta^{14}N$ isotope ratios to sample isotope ratios in per mil (‰):

$$\delta^{13}C \text{ or } \delta^{15}N = \left(\frac{R_{Sample}}{R_{Standard}} - 1\right) \times 1000 \text{ ,}$$

where $R = {}^{13}C/_{12}C$ for $\delta^{13}C$ and $R = {}^{15}N/_{14}N$ for $\delta^{15}N$

Runs began with a blank, followed by an acetanilide standard, and then the samples. Additional blank/acetanilide sets accompanied sample runs, with one after the 12th sample, and one upon completion of the 24 sample run. These blank/acetanilide sets were later compared with other samples for lipid correction of carbon signatures.

1.2.3 Statistical Analyses

Several steps were taken to prepare data prior to statistical analyses. First, diet data were pooled into coarser categories: chironomid, benthic microcrustacean (i.e. mostly chydorids), amphipod, isopod, mussel, zooplankton, and other. The “other” diet

category included prey such as gastropod, hydracarina, nematode, sphaeriid, and unknown insect and routinely constituted <10% of total diet biomass. Fatty acid data were expressed as percent composition (similar to Happel 2013). Fatty acids which made up < 1% of the total proportion of fatty acids (i.e. when averaged across all sites, dates, and fish sizes) and had low % variation were excluded from analysis due to their relatively low contribution (Happel 2013). Overall, fatty acids comprising >91% of total fatty acid composition were utilized in all analyses, including C14:0, 14 methyl-hexadecanoate, 15 methyl-hexadecanoate, C16:0, C16:1n-7, C18:0, C18:1n-9, C18:1n-7, C18:2n-6, C18:3n-3, C18:4n-3, C20:1n-9, C20:4n-6, C20:5n-3, C22:5n-6, C22:5n-3, and C22:6n-3.

Catches of Round Goby were inconsistent across space and time and large numbers of all three Round Goby size classes were not collected upon each sampling occasion. Thus, to facilitate comparisons across sites, seasons and size classes, data from different depths (3m, 7−9m, and 14−16m) were pooled. Initial examination of trophic indicators failed to reveal clear differences across depths, and Round Gobies are known to actively move between these depths (Kornis et al. 2012). Even after pooling by depth, data (diet, fatty acid, and stable isotope) were not balanced (i.e. did not have data coverage) across all site, season, and goby size category combinations. To visualize patterns, we initially included all 2010 data grouped by site, season and size class. Then, to allow for balanced analyses we only considered differences among intermediate size (60–100 mm) gobies collected during three seasons (May, July, and September) in 2010 at four focus sites: two western Lake Michigan sampling sites (FP, HP), one southern site (CA) and one eastern Lake Michigan sampling site (SA).

For diet and fatty acid data, Bray-Curtis similarity matrices were constructed with PRIMER-E (PRIMER-E Ltd., Plymouth, UK, version 6), first, using all 2010 data (data grouped by site, season and size class), and then using only the balanced data (60–100 mm gobies from the four focus sites). Two axis, non-metric multidimensional scaling (nMDS) plots (Cox and Cox 2008) were used to visualize multivariate patterns. Analysis of similarity (ANOSIM) (Clarke 1993) in PRIMER-E was used to test for significant differences among intermediate size (i.e. 60−100mm) gobies between the four focus sites and seasons. ANOSIM results were interpreted based on similarity/dissimilarity within and between pairwise groups (i.e. site, season, and goby size combinations). ANOSIM was appropriate for these data because it is a non-parametric test that adequately accounted for shortcomings in low sample size and sample imbalance between factors (i.e. sites, seasons, sizes) (Clarke and Gorley 2006) that were still present, but not as prevalent in some trophic indicator datasets. Cluster analysis results were overlaid onto nMDS and ANOSIM results to better visualize differences between sites and dates (Cox and Cox 2008).

Stable isotope results were graphed as biplots ($\delta^{13}C$ vs $\delta^{15}N$) and compared by site, capture date, and goby size category, first, using all 2010 data (data grouped by site, season and size class), and then using only the balanced data (60–100mm gobies from the four focus sites). Using the latter data set, we compared mean $\delta^{13}C$ and $\delta^{15}N$ stable isotope values among our sites and months using 2-way ANOVA (analysis of variance) tests in R statistical analysis software (Freeware: http://www.r-project.org/).

During 2011, we sampled a subset of the sites sampled during 2010. These sites were selected as part of a larger near-shore foodweb study, and we only collected Round

Goby from five sites (SB, FP, WB, HP and MC). We used the resulting diet, FAS, and SIR data from 2011 Round Goby to evaluate if spatial, seasonal and size class patterns were generally consistent across years. Specifically, we developed additional nMDS ordination plots using the 2011 diet and FAS data (see methods above). In addition, we developed SIR biplots ($\delta^{13}C$ vs $\delta^{15}N$) using 2011 data.

1.3 Results

Round Goby diet contents were highly variable over space, time, and by fish size. Chironomids were the most abundant food item for < 60mm gobies, while intermediate size Round Gobies (60−100mm) consumed a more diverse diet, including chironomids, benthic microcrustaceans, and dreissenid mussels. Large Round Goby (>100mm) diets contained greater proportions of dreissenid mussels, but chironomids and microcrustaceans were also present. While seasonal variation in diet contents appeared to be less of a factor than size (i.e. fish length), some seasonal trends were evident. For instance, relative consumption of benthic microcrustaceans by intermediate sized Round Goby increased from May to July and September, and relative consumption of dreissenids by large Round Goby increased from July to September. Site was a relatively important influence on prey consumption, with prey availability (i.e. benthos composition) seemingly influencing the type of prey consumed at a site. For instance, the benthic macroinvertebrate prey base at site SA was dominated by dreissenid mussels, and at this site Round Gobies of the two largest size classes (i.e. 60−100mm and >100mm) consumed mostly dreissenid mussels during all seasons. Relative abundances of

chironomid larvae were much greater at most other sites, and these prey were consumed at a relatively higher proportion (Figure 2).

Non-metric multidimensional scaling (nMDS) of all diet data from 2010 (i.e. fishes from all sites, seasons, and fish sizes available) further revealed spatial, temporal, and size-related variability that closely mirrored initial diet observations (Figure 3a). This nMDS matrix had a low to moderate stress score (0.12) indicating that the axes are interpretable. Similarly, the nMDS of diet data from intermediate size Round Gobies (60−100mm) collected at the four focus sites (i.e. FP, HP, CA, and SA) were characterized by a low stress score (0.04), and showed a clear differentiation among sites and seasons; FP, HP, & CA grouped together versus SA (global test sample statistic = 0.1%; R = 0.250 for FP & SA, R = 0.395 for HP & SA, R = 0.234 for CA & SA) and May, July, and September were all significantly different (global test sample statistic = 0.1%; R = 0.224 for May & July, R = 0.210 for May & September, R = 0.100 for July & September) (Figure 4a).

Dominant fatty acids in Round Goby tissues included C16:0, C16:1n-7, C18:1n-9, C20:5n-3, and C22:6n-3 (Table 2). The relative concentration of fatty acids appeared to vary spatially; for example, goby from SA contained particularly high concentrations of DHA and goby from HP contained particularly high concentrations of palmitic acid and EPA. Moreover, across all sites, Round Goby from sites along eastern Lake Michigan tended to contain high concentrations of DHA, while sites along western Lake Michigan tended to contain relatively high concentrations of palmitic acid and EPA (Table 2). Fatty acid composition was visualized using nMDS for all available 2010 profiles (i.e. fishes from all sites, seasons, and fish sizes available; Figure 3b). This nMDS matrix was

characterized by a low stress score (0.09) and generally demonstrated differentiation among eastern and western sites; with HP and SA extremely divergent in ordination space. The FAS nMDS matrix of 60−100mm Round Goby from focus sites also had a low stress score (0.09; Figure 4b). Examination of fatty acid data using ANOSIM and cluster analysis showed differences between all sites and seasons. HP & CA show the strongest contrast for adjacent sites (global test sample statistic = 0.1%; R = 0.682) and there was low variation between other adjacent sites (R = 0.306 for FP & HP, R = 0.382 for CA & SA). May, July, and September were all significantly different (global test sample statistic = 0.1%; R = 0.367 for May & July, R = 0.651 for May & September, R = 0.149 for July & September) (Figure 4).

Stable carbon isotope ratios revealed spatial patterns, suggesting that Round Goby from western Lake Michigan sites tended to rely more on benthic pathways, whereas eastern Lake Michigan sites tended to rely more on pelagic pathways. Stable nitrogen isotopic ratios were all roughly contained within the same trophic level and appeared to vary spatially, with lower $\delta^{15}N$ values for gobies collected in southwestern Lake Michigan (Table 2; Figure 5). Among 60−100mm Round Goby from focus sites, two-way ANOVA revealed that both $\delta^{13}C$ and $\delta^{15}N$ signatures were significantly different between all sites and seasons, with the strongest effect of site ($\delta^{13}C$, site, $F_4 = 78.765$, $p < 0.001$; season $F_2 = 3.425$ and $p = 0.037$; $\delta^{15}N$, site, $F_4 = 15.730$, $p < 0.001$; season $F_2 = 5.328$, $p = 0.006$).

Analyses of diet constituents, fatty acid profiles, and stable isotope ratios based on collections during 2011 revealed spatial patterns which were generally consistent with patterns observed for 2010; see comparisons of nMDS ordination plots and SIR biplots

among diet content, fatty acid, and stable isotope datasets (Figure 6). Since a subset of sites were sampled during 2011, nMDS ordination plots are not directly comparable among years. However, site-specific $\delta^{13}C$ and $\delta^{15}N$ values were very similar across the two years.

1.4 Discussion

Using three complementary trophic indicators, we describe variation in Round Goby trophic interactions across space, season and ontogeny in Lake Michigan during 2010. In particular, spatial patterns tended to be pronounced and reflect regional differences in feeding interactions, with pelagic production pathways being relatively important for Round Goby in the eastern region of Lake Michigan's south basin, while near-shore benthic production pathways appear to be more important in western Lake Michigan. Overall, our findings provide an understanding of the variable role of Round Goby in the emerging near-shore Lake Michigan foodweb. Moreover, this study highlights the utility of employing multiple trophic indicators for elucidating relationships in foodweb studies.

1.4.1 Spatial Patterns

All three trophic indicators demonstrate differences in trophic connections across locations. In general, in the southern basin of Lake Michigan the relative importance of pelagic pathways in supporting Round Goby appears to decrease from east to west. In particular, among our focus sites, SA was distinct from other focus locations, with a particularly strong influence of pelagic pathways. In contrast, western sites in Wisconsin and Illinois (FP and HP, respectively) were more influenced by near-shore benthic

pathways, while the southern site in Indiana (CA) was intermediate. We did not explicitly evaluate the mechanistic pathways that may have structured these spatial patterns in Round Goby trophic interactions. However, we speculate that they may be related to regional differences in dominant substrates, water circulation patterns and relative riverine inputs, which may collectively influence both the relative composition of invertebrate prey and the primary production pathways supporting prey production.

While diet contents varied seasonally and by Round Goby size, spatial diet patterns were also evident. For example, diets at site SA were characterized by relatively high dreissenid mussel consumption across seasons and sizes. The ordination and ANOSIM analyses of 60−100mm Round Goby from our focus sites clearly demonstrated that diets differed among sites. While the ordination of all Round Goby diets (regardless of site and size) is not as clear, this analysis is also suggestive of broad spatial diet differences, as many size and season combination values from the same sites grouped together in ordination space (e.g., FP and SA).

Fatty acid and stable isotope values reflected spatial patterns similar to spatial diet patterns. Moreover, FAS and SIR spatial patterns are even more distinct than diet patterns and reflect a greater reliance on pelagic pathways in eastern Lake Michigan, especially at SA. Since these trophic indicators reflect prey consumption over a longer time horizon, they likely better integrate long term differences in prey availability and production pathways and are likely not sensitive to potential short-term (e.g., inter-daily) variation in prey consumption. Spatial differences are strongly reflected in not only fatty acid and stable isotope signatures of 60−100mm Round Goby from focus sites, but also different sizes of Round Goby collected from throughout the lake. For stable isotopes, $\delta^{13}C$ is

higher on the east side of Lake Michigan, indicating reliance on the pelagic foodweb (i.e. likely including benthic mussels which sequester nutrients from pelagic environments). Fatty acid profiles were quite variable, but showed indications of the same east versus west gradient. For example, C22:6n-7 was particularly abundant in Round Goby collected from eastern sites. Past studies demonstrate that C22:6n-3 is reflective of pelagic production pathways (Czesny et al. 2011; Happel 2013). Similarly, C16:1n-7 and C20:5n-3 were particularly abundant in Round Goby collected from western sites, and these fatty acids are known to reflect more benthic pathways (Kelly and Scheibling 2012).

We examined a substantially broader spatial scale than other Round Goby trophic interaction studies, and the current study provides a new baseline for comparisons of Round Goby diet on such broad spatial scales. Raby et al. (2010) showed that Round Goby diets are quite variable between locations, even at relatively localized scales in the Trent River, Ontario, which was largely attributable to the benthic prey fauna available for consumption at each site. Round Gobies have a relatively small home range for most of the year (Ray and Corkum 2001; Lynch and Mensinger 2012), which will likely result in diet patterns reflective of proximate prey availability. Round Goby are known to display distribution events of approximately 50m per event (i.e., in roughly a day) (Lynch and Mensinger 2012). Thus, while Round Goby were likely able to move among our sampling depths within a site, distribution events are likely not frequent enough or of sufficient distance to move large numbers of Round Gobies among most of our study sites (which were 70−250 km apart). While it is plausible that during earlier life some Round Goby may have experienced an environment distinct from the environment of capture, such individuals would still likely have spent the preceding growing season

confined to the general region of the lake where they were captured. However, Round Goby commonly overwinter in offshore Lake Michigan; broad, seasonal movements are possible and individuals may not inhabit the same near-shore region from one year to the next (Kornis et al. 2012).

Near-shore substrates are highly variable throughout Lake Michigan, and provide diverse and complex habitats for benthic invertebrate prey organisms and likely provide a variable prey base for Round Goby (Botts et al. 1996; Kuhns and Berg 1999; Pothoven et al. 2001). In particular, in the southern basin of Lake Michigan rocky substrates are far more common on the western side of the lake, as compared to the eastern side (Waples et al. 2005). Past studies in Lake Michigan have described that amphipods, isopods, chironomids, and dreissenid mussels are particularly abundant on rocky substrates (Winnell and Jude 1987; Janssen and Luebke 2004; Creque et al. 2007). Over sandy substrates, benthic invertebrates are generally less abundant and characterized by relatively high numbers of chironomids and dreissenid mussels (Janssen and Luebke 2004). Round Goby tend to prefer rocky, bedrock substrates (Ray and Corkum 2001) and may benefit from the relatively high production and densities of invertebrates on such substrates. In fact, Great Lakes fishes are known to consume differential prey over various substrate types (Creque et al. 2010). Given that we used different sampling methods to collect benthic invertebrates from rocky and sandy substrates, prey density estimates may not be directly comparable among sites. However, we speculate that high potential prey abundance (e.g., over some rocky substrate sites) may strongly influence Round Goby prey selectivity. In contrast, when prey are limited, Round Goby seemingly consume benthic invertebrate prey in proportion to their availability. For instance, since

dreissenids and chironomids are environmentally available throughout most of Lake Michigan, eastern Lake Michigan gobies typically consumed more environmentally available prey (i.e. dreissenids and chironomids), whereas western Lake Michigan gobies more carefully selected for certain benthic prey (i.e. amphipods, isopods, etc.). To this point, a past study has shown that Round Goby in the Great Lakes will consume dreissenid mussels, but actually prefer other prey types (Coulter et al. 2011).

The potential influence of substrate on the regional trophic patterns we document is not straightforward. Our study sites were selected *a priori* to include a combination of rocky and sandy sites. However, most sites included a combination of substrates or were bordered by other substrate types. For example, our rockiest site in eastern Lake Michigan (SA) can essentially be characterized as a rocky island in a sea of sand. Thus, the regional differences in prey consumption may not simply reflect very local substrate conditions, but rather broader substrate conditions. Benthic algae are able to attach and grow on rocky substrate more effectively than on soft substrate, and accordingly, the benthic algae, *Cladophora* abounds in western Lake Michigan (Tomlinson et al. 2010). The observed relative high concentrations of fatty acids related to benthic production (e.g., EPA, palmitic acid) and enriched $\delta^{13}C$ in western Lake Michigan suggest that benthic primary production pathways are more important in this region and may reflect primary consumers relying on *Cladophora* and other near-shore benthic primary producers (e.g., Turschak et al. 2014).

Cyclonic and anti-cyclonic water circulation drive many physical processes in the Great Lakes, including nutrient transport and passive dispersal of small-bodied organisms (Kerfoot et al. 2008; Kerfoot et al. 2010). Lake Michigan's southern basin is

characterized by mean cyclonic near-surface circulation patterns (Beletsky et al. 1999). Frequently, circulation patterns, coupled with prevailing winds favor the formation of upwelling events in western Lake Michigan and down-welling events in eastern Lake Michigan (Höök et al. 2004; Plattner et al. 2006). Such upwelling and down-welling events have the potential to force cold, bottom waters or less dense, surface water close to shore, respectively. Simultaneously, upwelling and down-welling events may distribute nutrients and organisms (Schelske et al. 1971; Yaguchi 1977; Bell and Eadie 1983). Specifically, prevailing downwellings may bring offshore, near-surface materials (including primary producers) into the near-shore zone of eastern Lake Michigan, while upwelling events may concentrate benthic material in the near-shore zone of western Lake Michigan. In turn, primary consumers in these two regions may differentially rely on these two (pelagic versus benthic) production pathways. Therefore, prevailing water circulation patterns may not only influence the type of benthic invertebrates present in different regions of Lake Michigan, but may also influence their fatty acid composition and relative enrichment and depletion of $\delta^{13}C$.

Rivers and drowned river mouth lakes (DRML) may exert strong influence on the abiotic and biotic dynamics of near-shore Lake Michigan. The number and mean size of tributaries draining into the main basin of Lake Michigan are much greater on the eastern side of the lake versus western side of the lake. Thus, the influence of rivers and DRMLs on the near-shore zone is likely greater along the eastern coast due to a higher flux of water and suspended materials into this region (Herdendorf 1990). Nutrient and sediment loading from lotic systems to lentic systems may influence dominant local primary producers (Elser et al. 2007) and influence benthic prey through effects on available

sediment (Nalepa et al. 1998). Fatty acid and stable isotope profiles are known to vary spatially in large, open systems (West et al. 2006; West et al. 2010). We would expect that fish obtaining prey from riverine sources would display lower $\delta^{13}C$ values (Dufour et al. 2005), and consistent with this expectation Round Goby from eastern Lake Michigan are characterized by relatively low $\delta^{13}C$ values. Similarly, we would expect riverine inputs to influence fatty acid profiles as Larson et al. (2013) documented variation in total fatty acid concentration and fatty acid composition among river, river mouth and near-shore sites in Lake Michigan.

Round Goby trophic indicators for a subset of locations during a second year (2011) generally supports the spatial patterns documented during 2010. However, we suggest that these documented spatial trophic patterns should be examined across additional years to more broadly define their consistency. For example, as we speculate that water circulation and upwelling patterns may partially drive regional differences in trophic patterns, it would be interesting to evaluate if these patterns hold during years when circulation and upwelling patterns depart from average conditions. Moreover, we suggest that similar analyses of other species should elucidate the consistency of these patterns. To this point, Happel (2013) evaluated diets, fatty acids and stable isotope ratios of age-0 Yellow Perch (*Perca flavescens*) during fall 2010 and generally documented the same spatial patterns we describe for Round Goby (i.e., greater reliance on benthic production pathways in western, as compared to eastern Lake Michigan).

1.4.2 Season and Size Patterns

Past studies demonstrate that Round Goby diets change ontogenetically from various small food items to large dreissenids with increasing Round Goby size (Ray and Corkum 1997; Corkum et al. 2004; Campbell et al. 2009; Raby et al. 2010; Andraso et al. 2011). We observed small Round Gobies (<60mm) consume relatively low numbers of dreissenid mussels and high numbers of chironomids, benthic microcrustaceans and zooplankton. In contrast, dreissenid mussels constitute a high proportion of large Round Goby (>100mm) diets. Such increased reliance on dreissenid mussels would be expected to shift Round Goby fatty acid and $\delta^{13}C$ profiles towards a more pelagic signature. Consumption of zooplankton and benthic microcrustaceans (e.g, chydorids) by small Round Goby may partially explain the limited transition towards such a pelagic signature. While benthic organisms, chydorid fatty acid and stable isotope signatures will likely reflect pelagic prey sources, since their diet mostly consists of cyanobacteria and algae (Lemke et al. 2007).

Seasonal prey item availability and corresponding prey item characteristics likely strongly influence seasonal Round Goby dietary composition. For instance, Round Gobies start feeding on relatively large, benthic macroinvertebrates in May (i.e. such as chironomids, amphipods, isopods, and ostracods). However, later in July and September, benthic microcrustaceans emerge and start to appear in Round Goby diets. Benthic microcrustaceans were the most apparent, new food item that was seasonally incorporated into diets; herein, chydorids were the most plentiful type of benthic microcrustacean. Chydorids do not start hatching and become numerous in the environment until waters become warmer (Meyers 1984; de Eyto and Irvine 2001),

usually not until late spring, especially July (Whiteside 1974). Chydorid prominence in summer and fall diet contents was especially apparent in 60−100mm fishes. Large (>100mm) goby in particular consumed large proportions of dreissenid mussels during September, and relied more on chironomids during May and July. Dreissenid reproduction occurs during warmer, summer months (Ackerman et al. 1994; Ram et al. 2011), which leads to increased dreissenid biomass and a more variable size of dreissenid prey available during this period.

Stable isotopes and fatty acids showed evidence that they may vary with fish size, but some of these relationships remain unclear. For instance, fatty acids showed some size-based variation, but these trends could not be teased apart from the effect of space and time (i.e. season) or overall trends. Past studies suggest that as larger Round Goby consume more dreissenid mussels, their stable isotope profiles may shift towards more a pelagic signature (lower $\delta^{13}C$) and a higher trophic level (higher $\delta^{15}N$). While such size-based stable isotope patterns may be evident within a location and season, the influence of spatial differences in stable isotope profiles appear to override such effects when considering the entirety of the dataset.

1.4.3 Conclusions

In conclusion, the three diet metrics collectively documented spatial, seasonal, and size-based differences in Round Goby trophic interactions in near-shore Lake Michigan. Spatial patterns showed a gradient in trophic interactions among sites in the southern basin of Lake Michigan from west (benthic pathways relatively important) to east (pelagic pathways relatively important). We hypothesize that these patterns reflect

various factors, including substrate type, upwelling and downwelling frequency, and relative riverine inputs. Overall, this research provides an understanding of the variable role of Round Goby in the near-shore Lake Michigan foodweb. Additionally, results demonstrate the potential for broad scale differences in the pathways supporting production of a relatively recent invasive species and the utility of simultaneously quantifying multiple trophic indicators.

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1.6 Tables

Table 1. Sampling site descriptions from throughout Lake Michigan. Each site is represented by site name, site abbreviation, state, and dominant substrate type. Site abbreviations found in this table correspond with site abbreviations found in the other table and figures.

Sampling Sites	**Abbreviation**	**State**	**Substrate**
Sturgeon Bay	SB	WI	Rocky
Fox Point/Green Can	FP	WI	Rocky
Whitefish Bay	WB	WI	Sandy
Highland Park	HP	IL	Rocky
Dead River	DR	IL	Sandy
Calumet	CA	IN	Sandy/Rocky
Michigan City	MC	IN	Sandy
Saugatuck	SA	MI	Sandy/Rocky
Muskegon	MK	MI	Sandy
Frankfort	FF	MI	Sandy/Rocky

Table 2. Summary of fatty acid (FA) and stable isotope (SI) mean values by sampling site (all sizes and seasons are combined) for 2010 Round Goby. Also included are the number of fish used for each analysis (n) and fish size range (minimum, Min, and maximum, Max, total length, TL) both summarized by site. Muskegon (MK) did not have any Round Gobies caught in 2010 that were analyzed for fatty acids. Abbreviations for site names are found in Table 1.

	SB	FP	WB	HP	DR	CA	MC	SA	MK	FF
n FA	38	50	4	81	5	63	5	87	-	29
Min (mm TL)	41.0	50.0	60.9	48.7	61.7	50.0	81.0	46.0	-	47.8
Max (mm TL)	169.3	166.7	155.2	158.0	140.6	106.0	103.0	137.0	-	116.0
Lipid (%)	2.590	2.876	2.870	3.489	3.988	3.567	3.877	3.005	-	2.818
C12:0	0.029	0.012	0.007	0.003	0.003	0.022	0.000	0.000	-	0.000
C14:0	1.397	1.571	1.484	1.803	2.027	2.103	2.382	1.633	-	1.991
C15:0	0.557	0.336	0.405	0.399	0.545	0.589	0.588	0.580	-	0.631
C16:0	14.699	14.553	14.640	15.967	15.371	13.892	12.705	13.792	-	13.761
C16:1n-9	0.637	0.388	0.383	0.394	0.325	0.574	0.407	0.455	-	0.408
C16:1n-7	7.787	10.270	11.993	13.596	11.184	9.024	10.560	9.445	-	8.986
15-Me-hexadecanoate	1.553	0.945	1.040	0.893	1.057	1.700	1.631	1.830	-	1.771
14-Me-hexadecanoate	1.305	0.815	0.997	0.823	1.093	1.293	1.376	1.440	-	1.749
C16:2	0.397	0.782	0.724	0.844	0.769	0.638	1.047	1.276	-	1.432
C17:0	0.758	0.380	0.388	0.385	0.478	0.692	0.684	0.598	-	0.598
C16:3	0.333	0.651	0.428	0.507	0.468	0.451	0.122	0.482	-	0.426
C17:1	0.540	0.307	0.379	0.383	0.643	0.601	0.117	0.344	-	0.372
C18:0	5.674	5.529	4.829	5.270	4.923	5.162	4.411	5.328	-	4.609
C18:1n-9	10.072	7.885	7.455	9.058	9.717	9.320	10.136	8.450	-	9.309

C18:1n-7	5.857	7.029	7.539	8.378	8.588	6.769	7.018	5.646	-	5.404
C18:2n-6	5.116	3.888	3.381	4.644	5.344	4.111	3.589	2.633	-	3.719
γ-Linolenic acid	0.456	0.484	0.407	0.449	0.404	0.537	0.418	0.296	-	0.311
C18:3n-3	3.140	2.022	1.256	2.193	2.549	2.723	2.340	1.816	-	2.459
C18:4n-3	0.903	0.983	0.744	0.834	1.376	1.196	1.870	1.652	-	1.245
C20:1n-9	1.319	0.941	0.956	0.638	1.322	1.888	2.430	2.184	-	2.054
C20:2n-6	0.316	0.191	0.213	0.121	0.205	0.285	0.292	0.318	-	0.255
C20:3n-6	0.254	0.154	0.140	0.087	0.096	0.327	0.258	0.208	-	0.239
C20:4n-6	6.758	5.341	5.999	4.254	3.978	6.756	5.165	6.349	-	7.118
C20:3n-3	0.229	0.120	0.112	0.091	0.115	0.248	0.148	0.138	-	0.119
C20:4n-3	0.352	0.292	0.261	0.218	0.340	0.431	0.410	0.392	-	0.332
C20:5n-3	13.722	18.154	17.833	16.127	15.925	13.738	14.620	11.316	-	12.857
C22:1n-11	0.165	0.117	0.089	0.070	0.065	0.123	0.147	0.210	-	0.161
C22:1n-9	0.158	0.128	0.135	0.098	0.106	0.146	0.256	0.379	-	0.330
C22:4n-6	0.789	0.602	0.780	0.364	0.459	0.962	0.782	0.931	-	1.322
C22:5n-6	1.791	1.406	1.870	1.040	1.587	2.570	2.738	3.385	-	3.515
C22:5n-3	4.780	6.972	6.646	4.738	4.363	4.410	4.752	5.338	-	5.132
C22:6n-3	8.157	6.751	6.485	5.330	4.575	6.720	6.599	11.152	-	7.386

	SB	FP	WB	HP	DR	CA	MC	SA	MK	FF
n SI	20	49	13	22	7	45	5	32	3	15
Min (mm TL)	50.3	42.2	52.1	51.9	61.7	48.0	80.7	52.0	65.0	58.6
Max (mm TL)	130.0	166.7	155.2	122.3	95.2	106.0	102.9	140.0	68.0	116.0
Avg $\delta^{15}N$	8.598	8.416	8.266	7.869	8.659	9.129	8.306	8.916	8.910	7.779
Avg $\delta^{13}C$	-18.671	-18.005	-18.609	-18.077	-19.173	-19.921	-21.153	-23.241	-22.203	-20.572

1.7 Figures

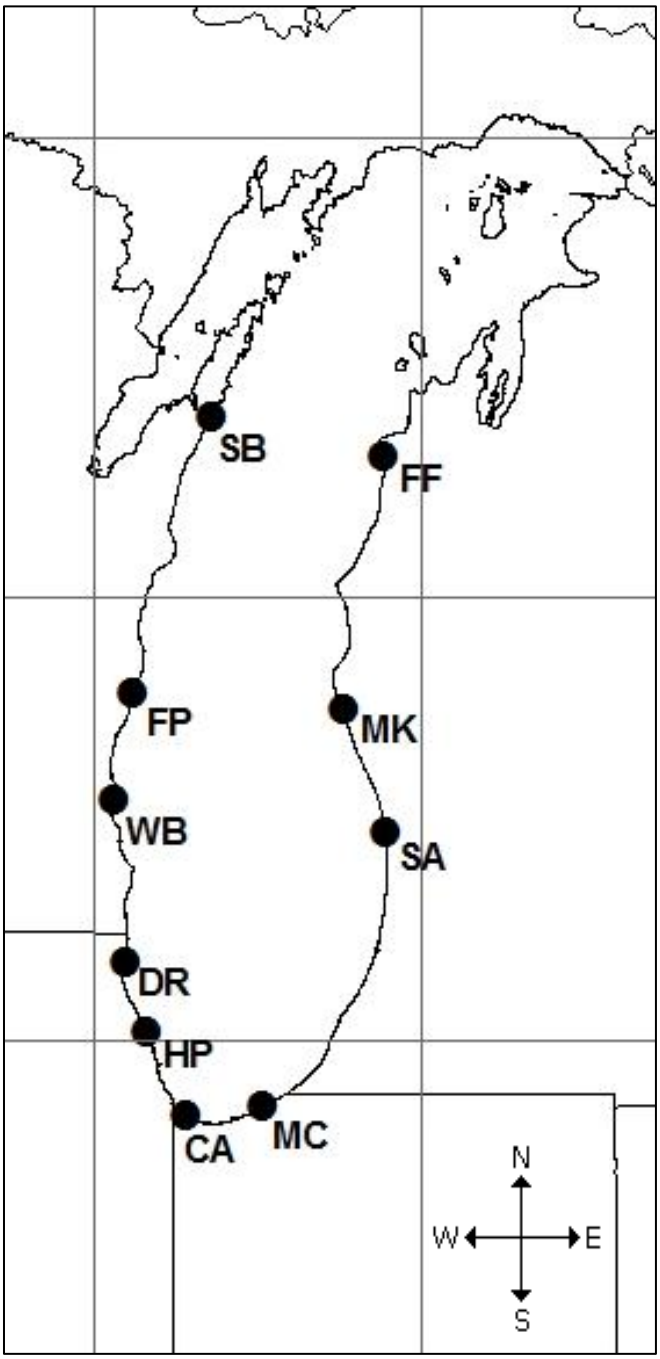

Figure 1. Sampling Locations within Lake Michigan during 2010−2011. Sites are identified with abbreviations that represent full site names, which are listed in Table 1.

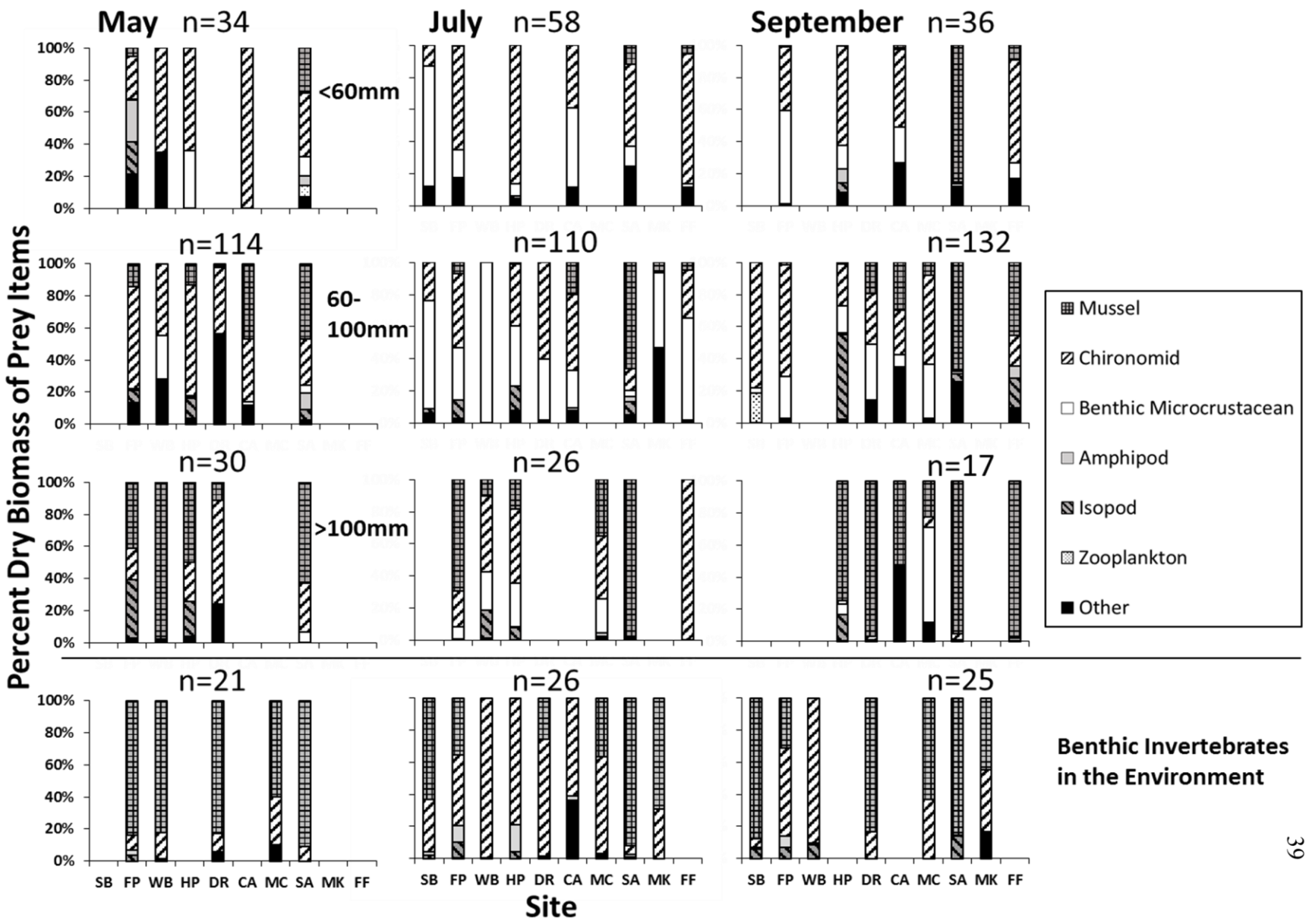
May n=34
July n=58
September n=36
<60mm
n=114
n=110
n=132
60-100mm
n=30
n=26
n=17
>100mm
n=21
n=26
n=25
100%
80%
60%
40%
20%
0%
Percent Dry Biomass of Prey Items
SB FP WB HP DR CA MC SA MK FF
Site
Mussel
Chironomid
Benthic Microcrustacean
Amphipod
Isopod
Zooplankton
Other
Benthic Invertebrates in the Environment

Figure 2. Round Goby diet (dry biomass; top three rows) and environmental composition of benthic invertebrates (dry biomass; bottom row) within near-shore Lake Michigan, 2010. Diet and benthic invertebrate biomass are presented by site (along the x-axes), season (left column, May; central column, July; right column, September), and fish size (i.e. for diet data only; top row, <60mm Round Goby; second row, 60–100mm Round Goby; third row, >100mm Round Goby). Sample sizes are presented with (n) as the number of Round Goby diets examined (top three rows) or number of benthic invertebrate samples examined (bottom row; petite PONAR or scraping with an airlift sampler). Sites are identified with abbreviations listed in Table 1. *The "other" category includes taxa that were found in low biomass in both Round Goby diets and benthic invertebrate samples; these taxa for diets include gastropod, hydracarina, nematode, sphaeriid, and unknown insect, whereas "other" benthic invertebrates includes crayfish, hydracarina, mollusk, gastropod, and leech.

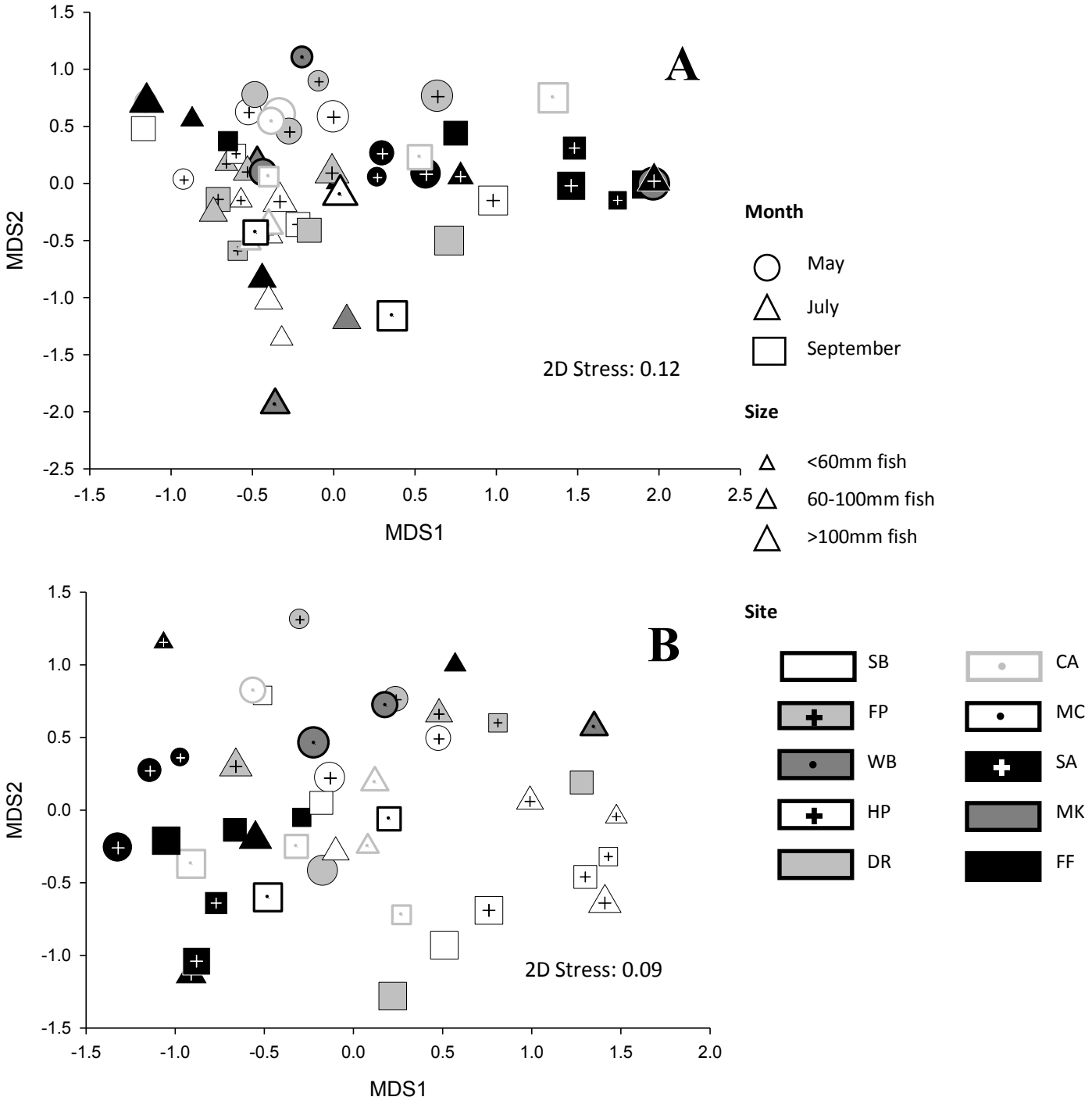

Figure 3. Non-metric multidimensional scaling (NMDS) by site (symbol fill), season (type of symbol), and fish size (size of symbol) for A) diet contents and B) fatty acids of 2010 fishes. Each data point represents the mean value in 2-axis ordination space for a particular data grouping. Sites are identified with abbreviations listed in Table 1.

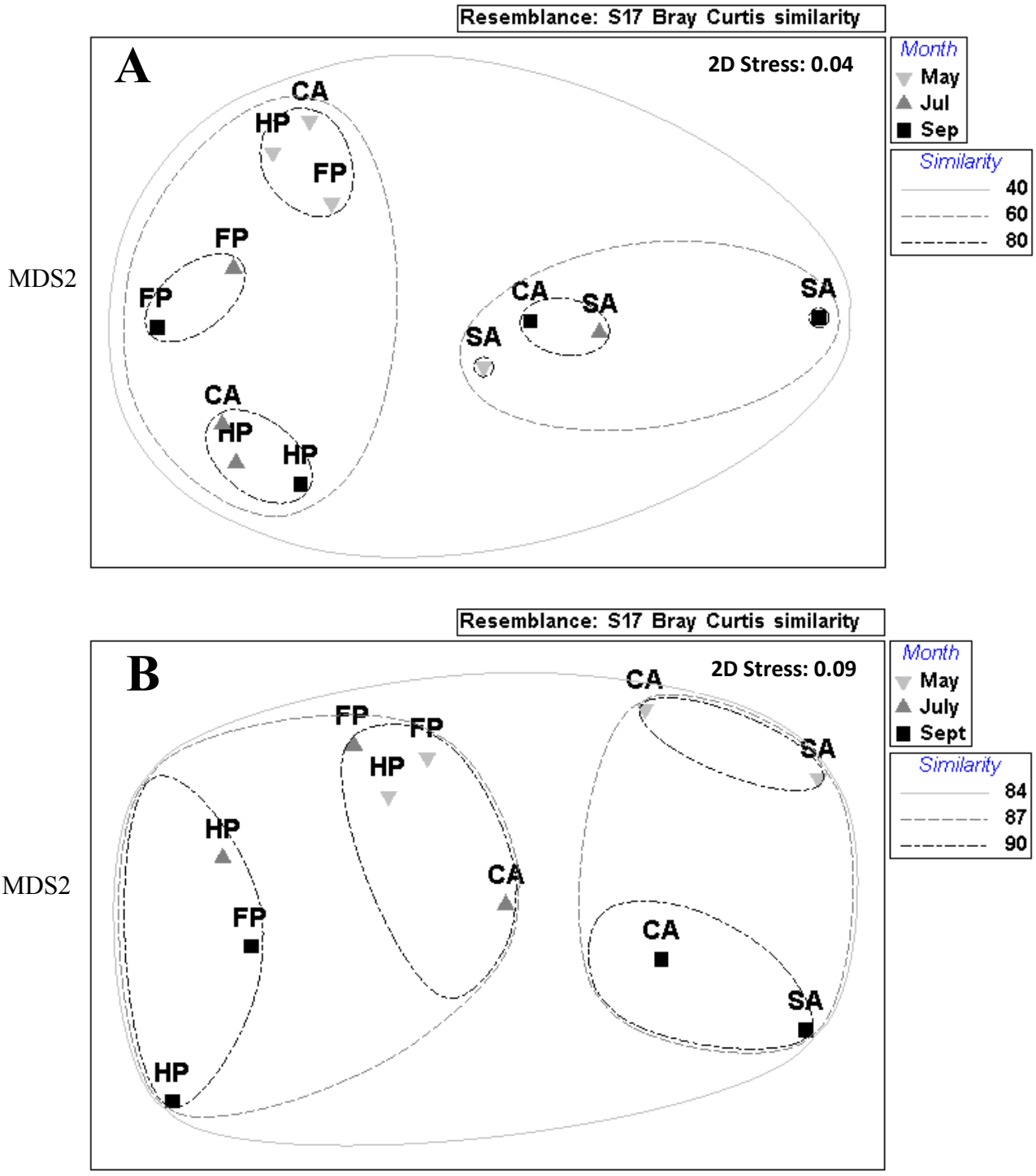

Figure 4. Analysis of similarity (ANOSIM) by site and season for 60–100mm Round Goby collected at the four focus sites during 2010, A) diet contents and B) fatty acids. Sites are identified with abbreviations provided in Table 1.

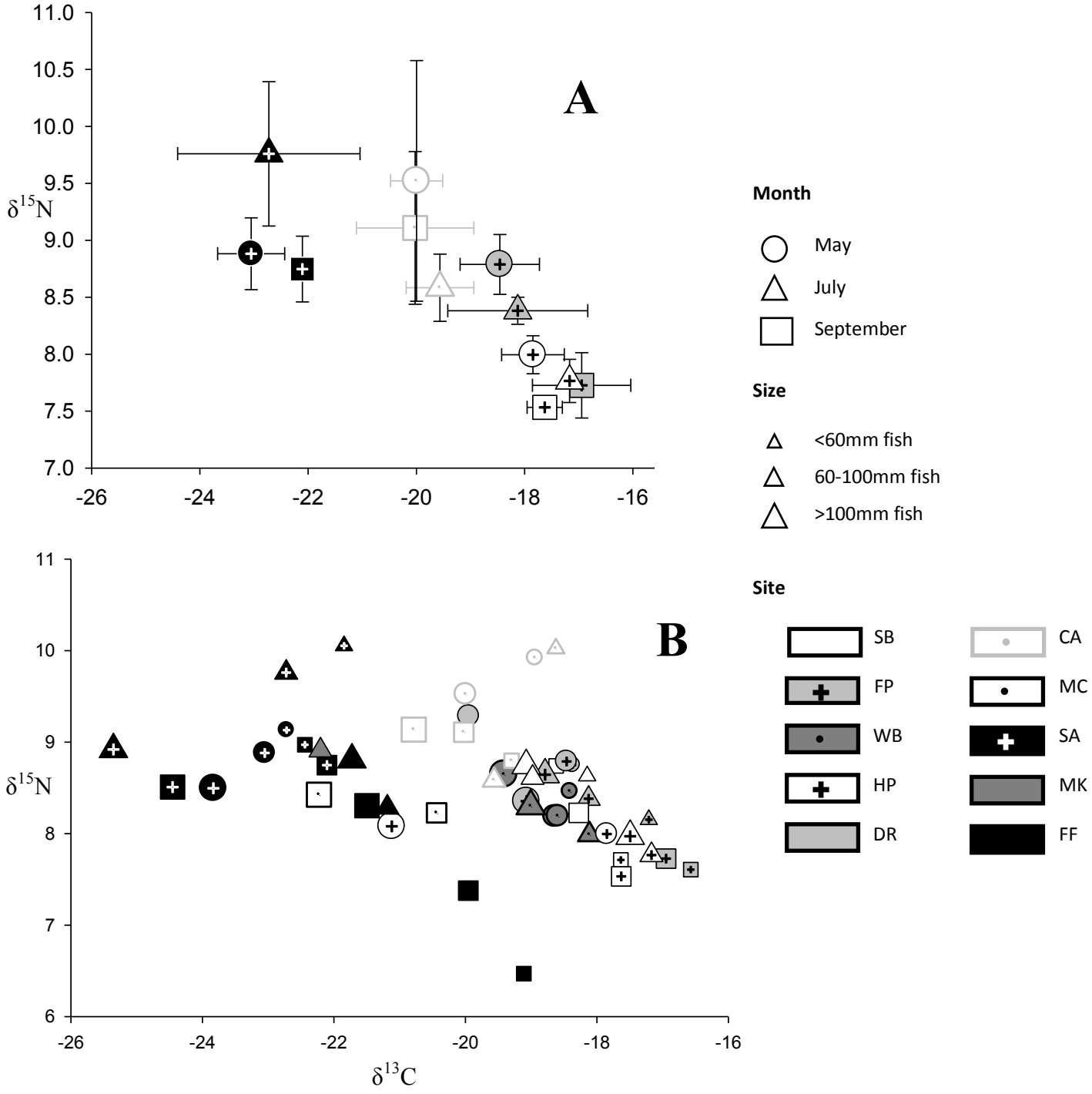

Figure 5. Stable isotope signatures by site (symbol fill) and season (type of symbol) for A) 60–100mm fishes from 2010 focus sites with standard error bars and B) all size (symbol size) fishes from all 2010 sample sites. Sites are identified with abbreviations that represent full site names, which are listed in Table 1.

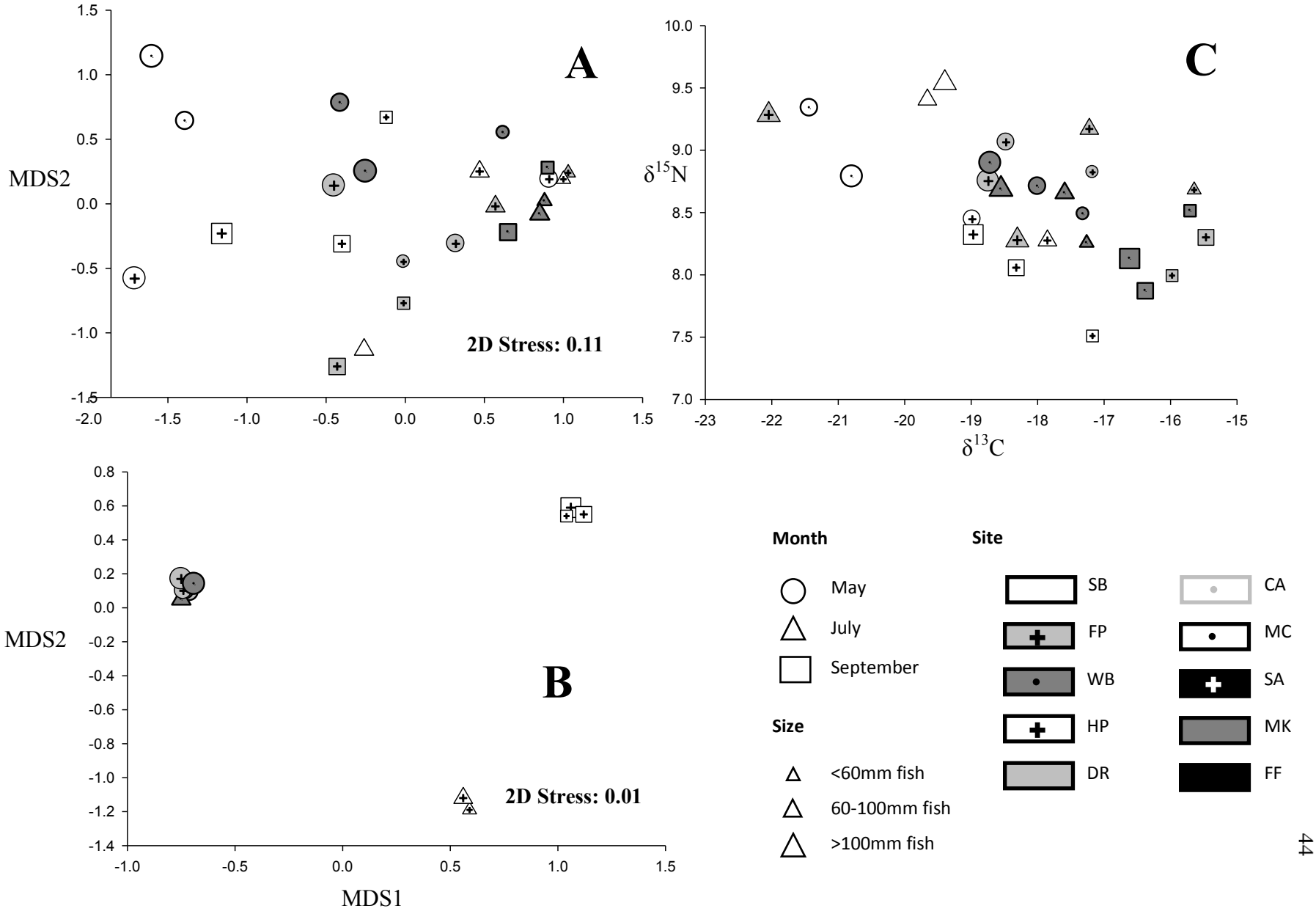
A
MDS2
2D Stress: 0.11
C
δ15N
δ13C
B
MDS2
MDS1
2D Stress: 0.01
Month
May
July
September
Size
<60mm fish
60-100mm fish
>100mm fish
Site
SB
FP
WB
HP
DR
CA
MC
SA
MK
FF

Figure 6. Non-metric multidimensional scaling (NMDS) by site (symbol fill), season (type of symbol), and fish size (size of symbol) for A) diet contents and B) fatty acids, and C) mean $\delta^{13}C$ versus $\delta^{15}N$, from 2011 (i.e., for inter-annual comparison with 2010). Sites are identified with abbreviations that represent full site names, which are listed in Table 1.

VITA

VITA

Michael Lee Henebry
Purdue University, Department of Natural Resources

Education
B.S., Biology, 2008, Roanoke College, Salem, Virginia
M.S., Fisheries and Wildlife Sciences, 2011, Virginia Polytechnic Institute and State University, Blacksburg, Virginia
M.S., Fisheries and Aquatic Sciences, 2014 (Expected August), Purdue University, West Lafayette, Indiana

Research Interests
Numerical / Quantitative Ecology
Ichthyology / Aquatic Ecology
Spatial and Temporal Variation in Foodwebs / Feeding Interactions
Multiple Trophic Indicators (Diets, Fatty Acids, Stable Isotopes)
Invasive Species Control and Management
Life History Trait Variation
Biological-Ecological Trait Associations
Landscape Ecology

Professional Experience
Graduate Research Assistant, Purdue University
Research Advisor: Dr. Tomas O. Höök June 2010-August 2014

Project: Defining the nearshore foodweb of Lake Michigan. This was a multiple year, collaborative study in which we used several trophic indicators with different temporal resolutions (i.e. diet analysis, stable isotopes, and fatty acids) to examine foodweb dynamics within and between species (i.e., especially invasive and native species, such as round goby, yellow perch, spottail shiner, and alewife). I focused mainly on round goby to see how an invasive, benthic fish can affect the near-shore foodweb through feeding interactions at broad spatial (most of the lake) and temporal scales (May-September). I also explored the role of fish size (mm TL) on spatio-temporal feeding interactions, especially when round goby makes distinct switches in prey types / items.

Graduate Teaching Assistant / Instructor, Purdue University
Faculty Advisor: Dr. John C. Patton Fall 2011, Fall 2012, Fall 2013
Course Taught: Ecology and Systematics of Fishes (sophomore-junior level undergraduate: FNR 242)
Description: Handled all aspects of teaching 3 laboratory sections of "Ecology and Systematics of Fishes." I setup and tore down laboratory exercises independently, taught laboratory sections, and created, administered, and graded class assignments, quizzes, and the final laboratory practical. I also collaborated with one other TA in 2013 to reformat and make the majority of the course presentation materials available online for the first time. I handled most other aspects of this laboratory as well, including interacting with students after class and during office hours.

Graduate Research Assistant, Virginia Polytechnic Institute and State University
Research Advisor: Dr. Emmanuel A. Frimpong August 2008-June 2011

Project:

Conducted field and lab research involving multi-scale spatial and intraspecific variation in fish traits. I examined large scale differences in life history traits, and small scale differences in age and growth, feeding, and life histories. I also examined biological and ecological trait associations. Research objectives were accomplished using self-collected field data, data collected while conducting other studies, and large amounts of data from pre-existing literature. Additionally, I assisted other lab members on their projects in the field including fish sampling, water quality, habitat assessment, etc.

Graduate Teaching Assistant, Virginia Tech
Faculty Advisor: Dr. Emmanuel A. Frimpong Spring 2010
Course taught: Fish Ecology (sophomore-senior level undergraduate)
Description: Worked with the instructor and another TA to coordinate class exercises, assisted students in and out of class, and graded tests/reports/summaries.

Graduate Teaching Assistant, Virginia Tech
Faculty Advisor: Dr. Emmanuel A. Frimpong Fall 2008 and Fall 2009
Course taught: Fisheries Techniques (sophomore-senior level undergraduate)
Description: Worked with other TA's and the instructor(s) to coordinate class and lab (fieldwork and laboratory) exercises, helped setup and take down labs, assisted students in and out of lab, and graded tests/reports/summaries.

Research Assistant, Roanoke College
Research Advisor: Dr. R.E. Jenkins May 2005-May 2008

Conducted field and lab research, wrote papers for publication on fishes of the family Catostomidae (suckers).

Projects:

Fecundity of the Sicklefin Redhorse, Carolina Redhorse, and Harelip Sucker, including aspects of Sicklefin Redhorse gonadal cycles

Food habits of the Carolina Redhorse

Age, growth, and maturation of the Bigeye Jumprock

Summer Funding:

Phillip C. Lee Jr., Endowed Research Scholarship Summer 2005
Roanoke College Trustee Research Grant Summer 2006 and 2007

Teaching Assistant, Roanoke College
Faculty Advisor: Various Fall 2006, Fall 2007, Spring 2006, Spring 2007
Courses taught: Biology 120 (Principles of Biology) and Biology 125 (Biodiversity) (Biology Major introductory sequence)
Description: Under the supervision of a faculty member, helped students in and out of lab with questions, prepped and took down labs, and graded assignments.

Marine Aquaria Supervisor, Roanoke College June 2005-July 2008
Description: Maintained all aspects of a 125 gallon marine aquarium system and certain other aspects of the freshwater aquaria in the department.

Awards

Purdue University Department of Forestry and Natural Resources Travel Grant ($300)
Fall 2011, Spring 2013
Virginia Tech Graduate School Travel Grant ($500, split with 3 other students)
Summer 2009
Gary Wesley Leonard Memorial Award in Biology
Spring 2008
Roanoke College Junior Scholar
Spring 2007
Roanoke College Biology Department Darwin Award for top students (3.0 GPA with at least a "B" in all science classes over 4 semesters)
Fall 2006
Roanoke College Dean's List of Distinguished Students
Fall 2005, Spring 2006, Fall 2007, Spring 2008
Roanoke College Faculty's List of Honorable Mention
Fall 2004, Spring 2005, Fall 2006, Spring 2007

Professional Associations

International Association of Great Lakes Research (IAGLR) Member
Spring 2013-Spring 2014
Description: Attended and gave an oral presentation at the international meeting in 2013.
Primary Editor, The Compass, Purdue University Department of Forestry and Natural Resources
Fall 2013-Spring 2014
Description: Handled all aspects of this department-wide outreach publication for 1.5 semesters, including soliciting, organizing, and editing articles.

Virginia Tech Chapter of the American Fisheries Society Member and Outreach Chair
Fall 2009-Fall 2010
Description: Chair of the outreach committee and member of the stream concerns committee. Managed the Virginia Tech American Fisheries Society listserv from Fall 2009-Fall 2011.

Technology Chair, Virginia Tech Fisheries and Wildlife Graduate Student Assembly (FiWGSA)
Fall 2009-Fall 2011
Description: Handled technology-related issues for FiWGSA and managed the FiWGSA listserv.

American Fisheries Society National Member
Fall 2008-present
Description: Participated in activities, meetings, and conferences; gave two presentations at the annual conference (2009 Nashville, 2011 Seattle).

Virginia Academy of Science Member
2006
Description: Presented a poster at the annual conference (hosted by Virginia Tech).

Local and National Member of the American Chemical Society
August 2004-August 2006
Description: Participated in many activities and meetings.

Other Skills/Certifications

PADI Open Water Scuba Certification
November 2007-present
Description: Completed the ≤60ft dive course, with 6 training dives.

Red Cross CPR and First Aid Certification
April 2011-present
Description: Completed the certification course twice to be up-to-date on several life-saving techniques for potential field and laboratory emergencies.

PUBLICATION

PUBLICATION

Frimpong, E.A., and Henebry, M.L. 2012. Short-term effects of formalin and ethanol fixation and preservation techniques on weight and size of fish eggs. *Transactions of the American Fisheries Society* 141(6): 1472–1479.